USAEHA

Laser Measurement Techniques Guide for a Hazard Evaluation

U.S. Army Environmental Hygiene Agency
Aberdeen Proving Ground, Maryland 21010-5422

Approved for public release; distribution unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp Date Jun 30, 1986

- **PORT SECURITY CLASSIFICATION**: CLASSIFIED
- **1b. RESTRICTIVE MARKINGS**:
- **2a. SECURITY CLASSIFICATION AUTHORITY**:
- **2b. DECLASSIFICATION / DOWNGRADING SCHEDULE**:
- **3. DISTRIBUTION / AVAILABILITY OF REPORT**: Approved for public release; distribution unlimited
- **4. PERFORMING ORGANIZATION REPORT NUMBER(S)**: Technical Guide No. 192
- **5. MONITORING ORGANIZATION REPORT NUMBER(S)**:
- **6a. NAME OF PERFORMING ORGANIZATION**: U.S. Army Environmental Hygiene Agency
- **6b. OFFICE SYMBOL** *(If applicable)*: HSHB -MR-LL
- **7a. NAME OF MONITORING ORGANIZATION**:
- **6c. ADDRESS** *(City, State, and ZIP Code)*: Aberdeen Proving Ground, MD 21010-5422
- **7b. ADDRESS** *(City, State, and ZIP Code)*:
- **8a. NAME OF FUNDING / SPONSORING ORGANIZATION**:
- **8b. OFFICE SYMBOL** *(If applicable)*:
- **9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER**:
- **8c. ADDRESS** *(City, State, and ZIP Code)*:
- **10. SOURCE OF FUNDING NUMBERS**:

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO

- **11. TITLE** *(Include Security Classification)*: DOD Laser Measurement Techniques Guide for a Hazard Evaluation
- **ERSONAL AUTHOR(S)**: erry Lyon
- **TYPE OF REPORT**: Technical Guide
- **13b. TIME COVERED**: FROM ______ TO ______
- **14. DATE OF REPORT** *(Year, Month, Day)*: 92, August
- **15. PAGE COUNT**: 30
- **16. SUPPLEMENTARY NOTATION**:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

- **18. SUBJECT TERMS** *(Continue on reverse if necessary and identify by block number)*:

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This technical guide provides uniform DOD guidance when performing radiometric measurements upon laser systems to conduct a hazard evaluation. This guide was prepared for the Laser System Safety Working Group to provide some joint service standardized techniques for laser measurements and the hazard evaluation of military laser systems. This technical guide should facilitate acceptance of hazard evaluations performed by other services. Although this technical guide could be applied to any laser system, it was developed primarily for outdoor military combat and training lasers and should be used when evaluating the engineering development, advanced developmnet, and production models.

- **DISTRIBUTION / AVAILABILITY OF ABSTRACT**: UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS
- **21. ABSTRACT SECURITY CLASSIFICATION**: UNCLASSIFIED
- **NAME OF RESPONSIBLE INDIVIDUAL**: Terry Lyon
- **22b. TELEPHONE** *(Include Area Code)*: (410) 671-5069
- **22c. OFFICE SYMBOL**: HSHB-MR-LL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

CONTENTS

DEPARTMENT OF THE ARMY
U. S. ARMY ENVIRONMENTAL HYGIENE AGENCY
ABERDEEN PROVING GROUND, MARYLAND 21010-5422

REPLY TO
ATTENTION OF

HSHB-MR-LL

August 1992

USAEHA TECHNICAL GUIDE NO. 192

DOD LASER MEASUREMENT TECHNIQUES GUIDE FOR A HAZARD EVALUATION

1. INTRODUCTION. This technical guide is intended to provide uniform DOD guidance when performing radiometric measurements upon laser systems to conduct a hazard evaluation. This technical guide was prepared for the Laser System Safety Working Group (LSSWG) to provide some joint service standardized techniques for laser measurements and the hazard evaluation of military laser systems. This technical guide is intended to aid planners of joint service laser exercises by providing uniform guidance. This guide should facilitate acceptance of hazard evaluations performed by other services. Although this technical guide could be applied to any laser system, it was developed primarily for outdoor military combat and training lasers and should be used when evaluating the engineering development, advanced development, and production models. Ideally data collected for any evaluation should be obtained jointly to obtain acceptance by each services health and safety consultants. The application of standardized measurement and reporting techniques will also facilitate acceptance.

2. HAZARD EVALUATION.

a. General. A hazard evaluation must include an evaluation of the performance characteristics of the laser system and any supporting test equipment (e.g., test sets, portable facilities, etc.). Output beam characteristics are measured and then compared to appropriate occupational exposure limits (ELs) or maximum permissible exposure (MPE) which are considered acceptable maximum limits for human exposure. The evaluation results in a hypothetical analysis which yields hazard distances which are the closest approach to an unsafe situation without actually being unsafe. For the purposes of this document, the potential hazards relative to radiant energy will be analyzed, other secondary hazards (e.g., electric shock, toxic materials, noise, etc.) require additional consideration. Appendix A contains some useful radiometric and photometric terms and units and their definitions.

b. Standards. Consensus exposure limits have been published by the American National Standards Institute (ANSI), and these form the basis for laser Els in each service. Details for selecting an appropriate EL are contained in ANSI Z136.1 (see reference 16a) and other service specific publications [e.g., TB MED 524 (see reference 16b)].

c. Calculations. Simply comparing the laser output beam characteristics to the EL may yield academic results since other environmental factors (e.g., atmospheric conditions, terrain features, etc.) can play a dominant role in establishing range control measures to prevent any potentially hazardous laser beams from leaving the installation confines. Any hazard evaluation must incorporate common sense logic since unique laser safety problems have occurred. One can become so involved in the mathematics of an evaluation that a potentially serious problem might be missed. Thus, this guide deals more with the common pitfalls in an evaluation rather than simply the mathematics. Complex computer programs, which can grind out an evaluation in lightning speed, need testing to ensure that the program performs as intended.

3. MEASUREMENTS VERSUS THEORY.

a. Laser Specifications.

(1) Much useful information can be obtained from the Program Manager (PM). Minimum contract specifications are selected by the government contractor so that the laser system can accomplish some intended mission in the field. These specifications are minimum requirements and are verified by the PM or manufacturer by making detailed radiometric measurements. Thus, considerable data may already exist.

(2) Many individuals have suggested that safety specialists employ this data and the specifications rather than obtaining independent measurements when performing the hazard analysis. Many important laser safety problems have been missed by PMs and manufacturers when measurements were performed to confirm specifications. A few problems which were discovered by laser safety specialists include: a black lens cover which transmitted the laser beam, a laser system which emitted multiple laser beams which were not aligned to the system aiming optics, and a laser system which could lase after the power switch was turned off. The MIL-STD-1425A was intended to alert PMs and manufacturers of these and other potential laser safety problems. Many laser safety problems continue to occur.

(3) The data provided by a PM may not accurately allow a good prediction of the Nominal Ocular Hazard Distance (NOHD). The data was generated to confirm that the laser system meets the specifications, and not that it might greatly exceed them in a certain percentage or a new production lot of laser systems. A safety specialist might be able to evaluate certain aspects of a system based on either specified characteristics or measurements performed by the manufacturer or PM; however, the results are likely to paint too rosy a picture when dealing with the actual safety of the device.

b. Laser Measurements.

(1) To confirm the existing data and to more closely simulate hypothetical exposure conditions for the eye, a safety specialist must take radiometric measurements.

Such data need not be exhaustive and evaluate every temperature or power supply variation and its effect on the output laser beam characteristics. Often this data can and should be obtained from the PM to evaluate its implications for laser safety.

(2) The mere fact that radiometric measurements have been performed does not ensure the validity of the data. The Law of Murphy lurks everywhere, and safety specialists must always be alert for errors in the measurement technique and computational errors. Most measurement errors are geometrical errors or detector limitations (e.g., clipped part of the beam, pumplight, detector saturation, polarization, etc.). Computational errors often include slipping a decimal point when a detector scale was changed but not recorded.

(3) Output variations have been observed between the Advanced Development Model, Engineering Development Model, and the Production Model of many laser systems. Deterioration might be expected after the device enters the field due to the rough handling experienced in such an environment. This appears to be less of a problem today than in the past. Furthermore, variations have been observed during the production phase possibly due to manufacturing improvements. Thus, it is important to revisit a particular laser system to ensure the validity of previous evaluations.

4. ASSISTANCE. The responsibility to evaluate the potential hazards from a laser system rests with particular activities within each service. When it becomes necessary to perform a laser hazard evaluation, these activities should be requested to perform the evaluation. Any new production models and other laser systems which have been in field use should be evaluated jointly by these service activities. The Laser Microwave Division of the U.S. Army Environmental Hygiene Agency (USAEHA) serves as the Army consultant for health and safety with lasers and can perform the required analysis. Information on how to obtain services can be obtained by calling DSN 584-3932. Similar service is provided by personnel at the Naval Surface Weapons Center, Dahlgren, Virginia, at DSN 249-8171 and the U.S. Air Force OEHL/RZN, Brooks Air Force Base, Texas 78235 at DSN 240-3486.

5. DETECTOR TYPES.

a. General. Many different types of radiometer detectors are commercially available. Since measuring instruments must be capable of measuring over a very wide range of power or energy values and over a large range of wavelengths, no single detector is capable of measuring every type of laser which might be encountered. However, a few carefully selected detectors can provide a trustworthy measurement capability for most common military lasers.

b. Thermal Detectors.

(1) With a thermal detector, the laser radiation is absorbed by a black surface and converted to thermal energy or heat; the resultant temperature rise in the absorber corresponds directly to the power or energy of the laser. A radiometer which employs a

thermal detector is called a calorimeter. Since the absorber is very black, not only within the visible region as perceived by the eye, but over a very large wavelength region, the detector has a nearly constant response at different wavelengths and can be calibrated electrically to read directly in watts or joules.

(2) Any window material placed in front of a thermal detector will greatly limit the detector's wavelength response, and the window may exhibit effects from cross polarization to the laser beam during calibration and testing.

(3) The two most common types of thermal detectors are thermocouples and pyroelectrics. These thermal detectors are very useful in the laboratory as standard detectors due to their longer term stability and wavelength independence. Pyroelectric detectors often are also piezoelectric detectors, and some have been observed to respond to sound waves.

(4) Since thermocouple detectors are very insensitive relative to the published safety limits and pyroelectrics are rather fragile, neither instrument has been routinely used for field measurements. Pyroelectric detectors are best suited to measure radiant exposures below 100 mJ/cm^2 from pulsed infrared lasers for which few detectors exist. Recent advances in electrometer noise allow investigators to employ thermocouple detectors to measure fairly low power levels. Unfortunately, most electrometers can not integrate the current and that can not be used to measure the energy from a single pulse.

(5) The total output energy or power of a laser rangefinder (LRF) or laser designator (LD) can best be accurately measured by employing a disc calorimeter.

c. Quantum Detectors.

(1) Quantum detectors are normally more sensitive than thermal detectors since they respond directly to incoming photons. Three types of quantum detectors are: the photomultiplier tube, the vacuum photodiode, and the semiconductor photodiode.

(2) The photomultiplier tube is very sensitive since the device actually amplifies the signal. This amplification has been useful in the laboratory to measure the attenuation of a protective filters. However, sufficient sensitivity normally exists with other quantum detectors to evaluate filter materials. The sensitivity of a photomultiplier tube is not required for field measurements, and such detectors are prone to problems in humid environments.

(3) Vacuum photodiodes and semiconductor photodiodes are sufficiently sensitive to allow measurements at levels near the Els and have been used routinely to conduct field measurements. These devices are usually very stable and rugged. The output signal from quantum detectors is either a current or voltage. Since the sensitivity is wavelength dependent, an appropriate calibration factor is necessary to convert the electrical parameter into useful radiometric units. Several commercial radiometers which employ vacuum photodiodes and semiconductor photodiodes are battery operated which is a highly desirable

feature when performing a field study. Power supply inverters have been used to supply 120 VAC to non-battery operated radiometers by using an automobile battery which greatly limits the mobility required for field measurements.

6. MEASUREMENT CONSIDERATIONS.

a. General. Field measurements pose many new problems for radiometers which are often designed to perform measurements in the laboratory environment. The primary considerations are listed below:

b. Background Illumination and Dark Current.

(1) Outdoor daylight illumination can make measuring the laser beam similar to "finding the needle in a haystack." Even diffused sunlight from an overcast sky can contribute orders of magnitude greater power than a potentially hazardous laser beam being measured. Another serious obstacle to daylight measurements is caused by a changing cloud cover which can drastically affect the ambient zero position on the detector readout.

(2) Many detectors provide some means to zero out the ambient background, otherwise a background reading must be subtracted from the measurement with the laser. Some commercial radiometers do not have sufficient range to zero outdoor daylight. The best way to obtain reliable field data is to perform most down range field measurements at night after the skylight has faded to a low background level.

(3) Quantum detectors may provide a small current even when no optical radiation is striking the detector. This is called "dark current." Failure to account for this dark current could result in erroneous radiometric data.

c. Detector Saturation or Damage.

(1) When a detector is saturated or damaged during a measurement, no warning is given, and the results suggest that a laser beam is safer than in actuality - - a potentially serious conclusion. Saturation effects have confounded even the most experienced personnel who were questioning the results obtained during a measurement. Inexperienced personnel might not question the results and come to an erroneous conclusion.

(2) All detectors can be damaged or give erroneous readings if the level of optical radiation exceeds the design limits for the detector. The investigator needs to be aware of the approximate maximum level to which the detector will be exposed. The detector's limits can normally be obtained from the detector's specifications sheet.

(3) Detector saturation (or nonlinearity) is of greatest concern when evaluating pulsed lasers which can have high peak powers (1 megawatt or more). Saturation results in the clipping of the top portion of a pulsed laser signal. Detector linearity can be tested by

inserting a calibrated attenuating filter in front of the detector to reduce the level falling on the detector's surface. If the reading drops by the attenuation factor, then the detector is operating in a linear manner.

d. Calibration Factors.

(1) Often radiometers with thermal detectors are calibrated either from electrical standards or optical standards and then serve as a transfer standard for calibrating radiometers with quantum detectors.

(2) Calibration factors for radiometers with quantum detectors are obtained by comparing the power or energy measured from a laser using the transfer standard to the electrical current or voltage produced by the quantum detector. This ratio remains constant over a large range of incident power (six orders of magnitude or more), at the particular laser wavelength. Normally, each laser wavelength measured will require a new calibration factor.

(3) Example: a Scientech 1-inch disk calorimeter measured 2.0 milliwatt (mW) from a stable CW He-Ne laser operating at 632.8 nm. An EG&G 580 radiometer system provided a reading of 2.30×10^{-10} amperes (A) for the same laser. The calibration factor was 1.15×10^{-7} A/W. During calibration it is necessary to account for any instability of the laser source and to ensure that the thermal detector is responding to the laser radiation and not optical emissions generated by the thermal environment. A water filter inserted between the laser and calorimeter is useful to block infrared emissions while passing laser wavelength in the range of 400 to 1400 nm. If another CW He-Ne laser produced a reading of 3.95×10^{-9} A on the EG&G, the power of this second laser would be 34.3 mW.

e. Electromagnetic Energy Rejection.

(1) Many detectors will respond to other forms of electromagnetic energy for which they are not designed, such as from a two-way handheld radio transceiver often employed to make field measurements. Out-of-band radiometer response is referred to as electromagnetic interference (EMI).

(2) Some lasers may emit optical pump radiation along with the laser beam which may be invisible to the eye but may be recorded by the radiometer employed for the measurement. Such radiation can be nearly eliminated by placing a calibrated narrow-band filter over the laser output. The filter must be designed to transmit the specific laser wavelength while rejecting adjacent sidebands. Many complexities and potential errors exist when collecting data through a narrow-band filter. It's usually better and simpler just to back the detector away from the laser by a few meters so the pump radiation is diminished by the inverse-square law. The laser beam usually remains collimated. The laser beam usually does not follow the inverse-square law when using a large aperture detector out to a distance of a hundred meters or more.

(3) Most pyroelectric detectors respond to impulse noise sources which can combine with the radiometric quantity to give an erroneous reading. Readings using certain pyroelectric detectors have even been observed during nearby casual conversation.

(4) It is important to test the radiometer against possible nonlaser emissions from the laser system under test and the test environment. One simple test involves placing an opaque material in front of the radiometer detector which is known to pass radio frequency and sound energy. If the instrument does not respond during lasing with the material in place, then the radiometer can be used without further precaution.

f. Environmental Factors. High humidity inside the detector housing can affect the reliability of data. Atmospheric humidity can increase with the normal reduction in ambient temperture after sunset. Humidity can also enter the dectector housing through contact with the earth. Some variabilty of instrument response is also present with a variation in ambient temperture. The response of battery-operated equipment can change with severe battery depletion and the rate of battery depletion will usually be increased with a drop in temperture.

7. COMPLIANCE WITH MIL-STD-1425A.

a. Military Exemption. Most military lasers are exempt from the federal regulation (21 CFR 1040, see reference 16c) which requires that certain safety features be built into laser products sold in the U.S.

b. MIL-STD-1425A Requirements.

(1) Alternative design requirements for laser system safety features are contained in MIL-STD-1425A (see reference 16d). MIL-STD-1425A also contains design requirements for associated support equipment and laser facilities. When performing a hazard evaluation upon an exempted laser system, it is necessary to ensure that the requirements of MIL-STD-1425A have been applied.

(2) Some requirements contained in MIL-STD-1425A are: proper labeling and location of controls, elimination of unintentional output, extraneous radiation, or unwanted modes, proper use of interlocks, protection of optical sights, control of associated hazards, design of laser fire switch, a remote control connector, boresight retention, an emission indicator, pointing stability, training mode requirements, and special requirements for very high power lasers.

(3) A useful safety design checklist (see reference 16e) has been prepared by NSWC, Dahlgren, Virginia. This document provides a convenient data sheet which can be used to evaluate a laser system based upon MIL-STD-1425A.

c. <u>Hazard Classification</u>. The requirements contained in MIL-STD-1425A for a particular laser system require that the laser first be classified from a hazard standpoint according to ANSI Z136.1 (see reference 16a). Each service has agreed previously to follow the MPEs within this consensus standand.

(1) The required safety features contained in MIL-STD 1425A depend upon the degree of hazard posed by the laser. A detailed description of the classification system is beyond the scope of this document. For a strict analysis, the reader is referred to ANSI Z136.1.

(2) The classification for most military lasers can be obtained from the laser wavelength, pulse width or exposure duration, pulse rate for pulsed lasers, beam radiant energy or radiant power, exit beam diameter, and exit radiant exposure or irradiance. Additional information would be required for pulsed lasers with varying pulse rates, extended-source lasers, and for scanning laser systems.

(3) Most fielded military lasers fall either into the Class 3b or Class 4 hazard category. The development community is being pressed by field users to produce totally safe laser systems, and it has responded with new technologies. These often employ a 1,540 nm operating wavelength or means to produce a less hazardous extended source.

(4) A brief description of the classification system is provided in the following paragraphs.

(a) Class 1 laser devices are those <u>not</u> capable of emitting hazardous laser radiation under any operating or viewing condition.

(b) Class 2 laser devices are low power (less than 1 mW) CW visible (400 nm - 700 nm) laser devices. Precautions are required to prevent continuous staring into the direct beam; momentary (less than 0.25 sec) exposure occurring in an unintentional viewing situation are not considered hazardous.

(c) Some CW visible, Class 3a laser devices are considered safe to view with the unaided eye (as are Class 2 devices) since the exposure averaged over a 7-mm pupillary diameter is less than 1 mW. To qualify as a Class 3a laser, the power or energy must not exceed five times the accessible emission limit (AEL) for Class 1. Therefore, while not usually considered hazardous for unaided viewing, the laser must not be viewed from within the direct beam with magnifying optics.

(d) Class 3b laser devices are potentially hazardous if the direct or specularly reflected beam is viewed by the unprotected eye, but such a laser does not (unless focused) cause hazardous diffuse reflections. Care is required to prevent intrabeam viewing and to control specular reflections.

(e) Class 4 lasers are those pulsed visible and near-infrared lasers capable of producing diffuse reflection hazards or those lasers with an average output power of 500 mW or greater. Safety precautions associated with Class 4 lasers generally consist of using door interlocks to prevent accidental exposure of unauthorized or transient personnel entering the laser facility; the use of baffles to terminate the primary and secondary beams; and the wearing of protective eyewear (and clothing in a few cases) by personnel.

8. LASER SYSTEM POINTING ERRORS.

a. Pointing Accuracy. Knowing the laser hazard classification and the NOHD does not provide enough information for safe operation of a laser. Perhaps the most important aspect for range safety is the ability of an operator to point the laser toward a target while ensuring that the beam is terminated within the controlled area. Thus it is imperative to evaluate the pointing accuracy of a laser device. This usually requires that the laser be directed toward a downrange target in normal fashion while observing for boresight displacement and the degree of beam wander. A 1 meter square white target board with 10 cm grid lines is a useful target for evaluating pointing accuracy. Pointing accuracy for a safety evaluation considers errors other than ideal operation.

b. Data Collection. A laser system might not be able to achieve its intended mission if its beam could not be directed accurately toward a target. Often the PM can provide data related to system pointing and this should be reviewed when performing a hazard evaluation. Check automatic tracking systems to ensure that if they break lock with the target that they do not continue to fire the laser in some new direction during a maneuver. When obtaining pointing data, try to simulate a variety of realistic maneuvers.

c. Analysis. As a rough rule-of-thumb, the extent for a conservative angular buffer zone is 5 to 10 times the sum of the laser beam divergence plus the nominal worst-case pointing accuracy which includes human errors with tracking and boresight errors with the laser system. In general, only a 2-mil buffer zone has been required for lasers with a stabilized platforms; a 5-mil zone for moving stabilized lasers; and a 10-mil zone for handheld devices.

d. Other Precautions. Uncertainties in target recognition and operator skills may require the local laser range safety officer (LRSO) to add additional buffer requirements. Complete control of laser beams from automatic tracking systems might be accomplished by using baffles to restrict the beam when the required buffer is not available.

9. LASER PROTECTIVE EYEWEAR.

a. General. Another major aspect of a laser system hazard evaluation is to determine the minimum optical density (OD) for laser eye protection to ensure that a wearer located within the beam is afforded sufficient protection to preclude an exposure exceeding

the applicable ELs. Since many field tests are conducted at dusk or during periods of darkness, the adverse effects caused by reduced vision should also be evaluated.

b. Optical Density. The OD should be calculated from the worst possible exposure conditions, e.g., assuming a 7-mm pupillary diameter and a 5 or 8-cm collecting optic placed at the laser exit port. This information might be suitable guidance for maintenance personnel. When personnel can be located at various distances from the laser, the OD versus range could be graphically plotted for unaided and optically aided viewing. A clear atmosphere should be assumed and a typical worst-case optical sight that might be realistically encountered (i.e., 7 × 50 binoculars with a transmission of 70 percent in the near-infrared). Such a graph might allow the selection of eye protection which affords improved visual transmittance. Selecting the minimum OD necessary for protection will usually afford higher visual transmission which might have some secondary safety benefits. Unfortunately, when laser protective eyewear is procured, the optical density requirements cannot be specified precisely and sometimes much greater density than is required will be obtained.

10. LASER BEAM DIVERGENCE.

a. General. The laser beam divergence or angular beam spread must be determined to estimate the NOHD for a laser system. Beam divergence can be determined from field or laboratory measurements. The beam divergence can best be determined by taking radiometric measurements on a clear day at various distances from the laser output to a distance where the beam irradiance or radiant exposure has dropped to the exposure limit. This may not be practical with lasers having an NOHD in excess of 5 km. The radiant exposure or irradiance at near distances should be measured using a 7-mm circular aperture to depict unaided viewing and with an 5 or 8-cm circular aperture to depict telescopic viewing. An aperture larger than 7 mm may be necessary at the farther distances to average the effects from atmospheric turbulence.

b. Measurement Conditions. Radiometric measurements should be conducted during a mild evening where little ground haze is observed and preferably the laser should be operated from an elevated position to avoid atmospheric turbulence. The atmospheric extinction coefficient can be estimated by determining the atmospheric visibility. Sometimes, the weather service at a local airport can provide the visibility. Measurements should be conducted at approximate logarithmic distances, such as 1 m, 3.5 m, 10 m, 35 m, 100 m, 350 m, 1,000 m and greater to allow the evaluator to determine if the beam is focused in the near field and to predict the NOHD if it is beyond the farthest distance at which a measurement is made. Data obtained at these distances improve appearance and spread when the data is plotted on log scales.

c. Laboratory Measurements. The beam divergence for laser systems which are broader than 0.5 mrad can be measured in the laboratory by using a long focal length lens or concave mirror. The lens or mirror should have a focal length of 4 m or longer to measure

the divergence from most laser systems. The focal spot is directed toward a small circular aperture of known diameter located at the geometrical focal length of the lens. The fraction of the laser power calculations for beam divergence are contains in paragraph 11 b(1). A useful aperture set ranges from 0.1 to 0.25 cm diameter. The effective divergence to 1/e-points is related to the aperture diameter which passes 63 percent of the beam. The beam divergence in radians can be computed from the ratio of the aperture diameter for 63 percent transmission to the lens focal length.

11. GENERAL LASER RANGE EQUATION.

a. Gaussian Beam Distribution.

(1) Laser beams do not have well-defined edges as they exit from the laser cavity. Most are more intense at the center of the beam and gradually decrease outward. A Gaussian beam is one in which the irradiance variation follows the "error" function as given below in equation (1):

$$E = E_0 e^{\frac{-4\rho^2}{D_L^2}} \tag{1}$$

where $\rho = D_L/2$ when $E = E_0/e$. This equation is presented graphically by the solid curve of Figure 1. The ρ represents the distance radially from the center of the beam and D_L is the diameter at 1/e peak irradiance points.

(2) The initial beam diameter, a, is defined for hazard evaluation in such a manner that it contains 63 percent of the beam power which is the area under the curve. This value of beam diameter is referred to as the diameter at 1/e points. By using the 1/e-points beam diameter and the total output power or energy, the peak irradiance or radiant exposure in the beam can be computed from equations (2):

$$E = \frac{1.27\Phi}{a^2}, \quad H = \frac{1.27Q}{a^2} \tag{2}$$

(note that $1.27 = 4/\pi$).

(3) This concept can be visualized more clearly with a rectangular profile in Figure 1 which has the same total area under the curve as the Gaussian but with a dimension of l/e. Note that the peak value is the same between the two distributions. Assuming that most laser beams are Gaussian yields a reasonable approximation of beam diameter even if the beam shape is not truly Gaussian.

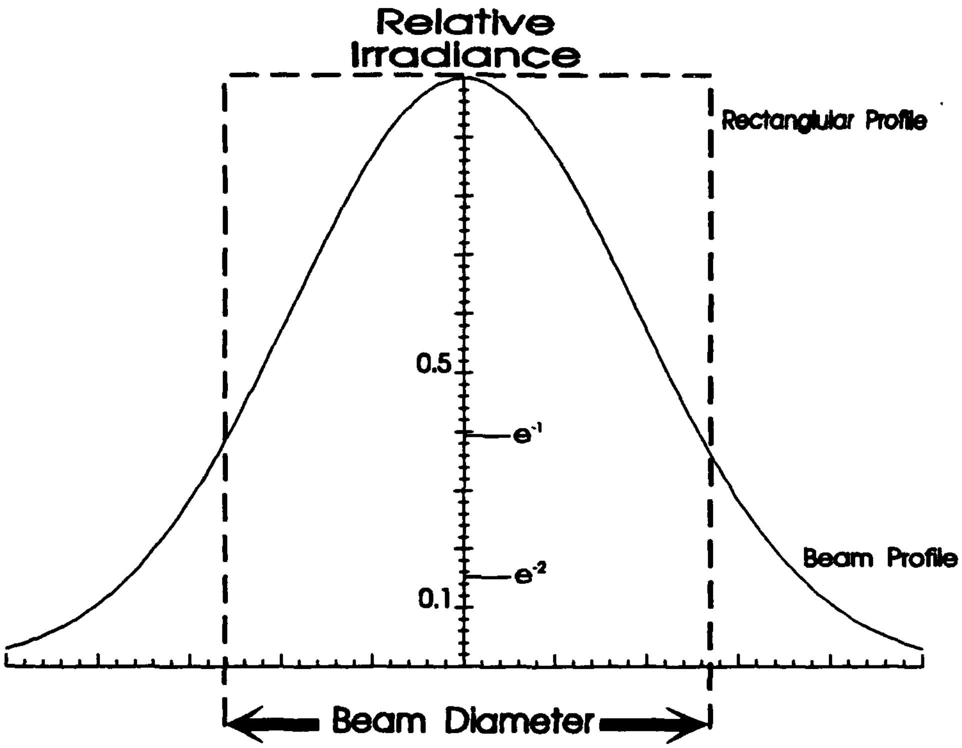

Figure 1. Ideal Gaussian Beam Distribution and a Rectangular Beam Profile Which Has the Same Peak Irradiance

b. Beam Divergence.

(1) Laser beam divergence should be determined at l/e points since the peak beam irradiance or radiant exposure can then be determined at any distance from the laser. One method to determine beam divergence is to measure the l/e-diameter at a distance away from the laser and then calculate the angle at which the beam spreads from:

$$\phi = \frac{\sqrt{D_L^2 - a^2}}{r - r_0} \tag{3}$$

where r_o is the distance from the laser to an external beam waist, if any. If an external beam waist does exist, then "a" refers to the diameter at the waist rather than the initial beam diameter.

(2) The beam diameter from any distance from the laser, D_L is, therefore, given by:

$$D_L = \sqrt{a^2+(r-r_0)^2\phi^2}\ . \tag{4}$$

where "a" could represent either the diameter of the beam at the laser exit port or the diameter of an external beam waist if present. The "r" represents the distance to the second measuring point, and "r_o" represents the distance to an external beam waist, if any.

(3) Normally the beam divergence specified by the laser manufacturer or the developer is given to l/e^2 points which allows one to determine the average irradiance downrange rather than peak irradiance. The peak irradiance is more of interest from the standpoint of a potentially hazardous exposure to the skin or eyes. For a gaussian beam the divergence specified at $1/e^2$ points can be divided by $\sqrt{2}$ to obtain the diverge at $1/e$ points.

(4) Often the beam divergence can be checked by visually observing the beam spot size on a target board with a grid pattern. Accounting for the fact that the eye is a nonlinear detector, the effective beam diameter to 1/e-points may be approximately 0.7 times the observed diameter. The divergence in radians is simply the effective diameter divided by the distance between the laser and the target.

c. The Laser Range Equation.

(1) The range equation in equation (5) (reference 16h) predicts the beam irradiance, E, at any distance from the laser using the output laser characteristics and the beam divergence.

$$E = \frac{1.27\,\Phi\, e^{-\mu r}}{a^2 + (r - r_o)^2\,\phi^2}\,. \tag{5}$$

(2) This equation applies strictly for peak data only and provides a fair approximation for irradiance data measured through an aperture. Atmospheric effects may exaggerate the peak data and use of an aperture will average somewhat the localized concentrations within the laser beam which are created by the atmosphere.

(3) Atmospheric attenuation can have a significant effect, especially at longer ranges, even in clear, nonturbulent air. The effects from the atmosphere are less noticeable within several hundred meters. Saturation of the magnitude of scintillation occurs at approximately 700 m. At greater or lesser ranges the variation of localized irradiance (or radiant exposure) values decreases. The range equation contains the term, $e^{-\mu r}$, to allow for the attenuation loss introduced by the atmosphere, where μ is the atmospheric attenuation factor. The theoretical peak irradiance at any range is the output power (reduced by atmospheric absorption) divided by the area of the beam to 1/e-points.

(4) Likewise, equation (5) can be rearranged to solve for the effective beam divergence, ϕ, from measured values of peak beam irradiance or radiant exposure. Irradiance or radiant exposure data obtained at long ranges can be used to determine the beam divergence using a graphical best-fit approach while selecting a realistic atmospheric attenuation coefficient for the measurement environment. Other general laser range equations take into account the entrance aperture size of the detector relative to the beam diameter and are published in the literature. See references 16f-h for additional details.

12. EXIT BEAM DIAMETER.

a. Beam Profile. An initial task important to a laser hazard evaluation is to determine the shape of the laser beam. A visual examination, using appropriate image converters and protective measures, can be used as a rough guide to evaluate the beam profile. If sufficient power exists, a rough picture of the output beam shape can be recorded on a thermally sensitive paper placed perpendicular to the beam size.

b. Clear Exit Aperture. It is often useful to measure the clear exit aperture diameter for future reference. The clear exit aperture can normally be measured with a metric ruler placed against the face of the output lens. Operation of the laser can be used to confirm that the exit lens limits the output beam.

c. Beam Diameter Measurement. If the beam is fairly circular, an estimate of the beam diameter at l/e-peak-irradiance-points can be approximated by measuring the total output power and then centering a variable diameter circular aperture over the output. When the aperture is positioned to maximize the reading and adjusted to pass 63 percent of the total radiant power, the diameter should be nearly the l/e-diameter referred to as the effective emergent beam diameter.

d. Gaussian Beams. If the output beam is strictly Gaussian in shape then its diameter might also be estimated by dividing the manufacturer's specified effective beam diameter at $1/e^2$ points by $\sqrt{2}$. The exit beam diameter specified by the developer is normally to $1/e^2$ points which allows one to predict the average irradiance rather than peak value. Figure 2 illustrates the fraction of a Gaussian beam that passes through a circular aperture.

e. Non-Gaussian Beam. If the beam is not circular, then further analysis would be required depending upon the degree of departure from a Gaussian shape and the size of the beam. Non-Gaussian laser beams can be treated as Gaussian beams in terms of effect upon the eye or skin in the far field to determine an effective exit beam diameter and an effective bem divergance. Irradiance or beam radiant exposure data should be relied on in the near field since existing laser range equations may not adequately predict a potentially hazardous exposure.

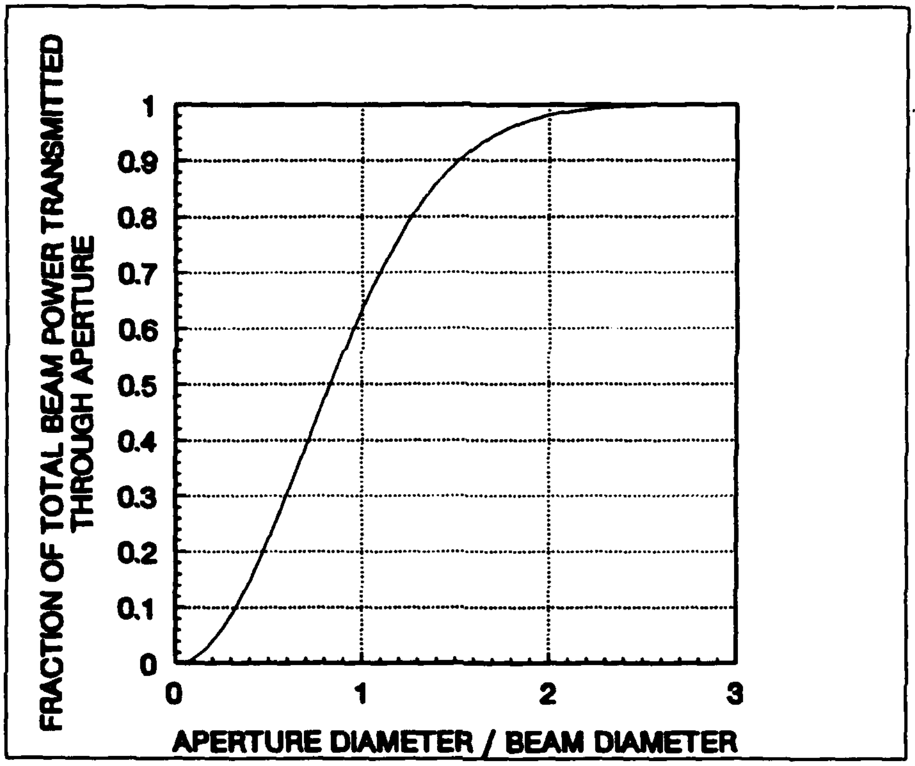

Figure 2. Percentage of Power Transmitted Through a Circular Aperture When Placed Centered Within a Gaussian Laser Beam as a Function of Relative Aperture Diameter

13. RADIANT POWER OR ENERGY.

a. Collateral Radiation.

(1) First, it is necessary to determine if all the output radiation is contained in only one beam and to account for any pump light or extraneous (collateral) radiation which may add unnecessarily to the measured output. When a laser system is found to emit multiple beams, each beam must be evaluated independently. Simply viewing the beam falling upon a white target in a dark environment with the unaided eye or with a near-infrared viewer provides a quick check to assess pump light and to detect other off-axis secondary beams. A laser attenuating filter may be necessary to permit safe viewing of the laser beam reflection. The attenuating filter should pass most visible radiation while attenuating the laser wavelength.

(2) Infrared lasers can be checked by other forms of thermally sensitive materials. If pump radiation is detected, a suitable method should be used to account for it during the laser beam measurement.

b. Measurement of Power or Energy.

(1) The first task when making a measurement of power or energy is to locate the beam. Locating a potentially hazardous laser beam, even when visible, can be difficult while wearing laser protective eyewear. Laser beams operating from 400 to 1,100 nm can be viewed with near-infrared conversion devices through protective eyewear. Near-infrared phosphor cards can be excited from a source of ultraviolet to view a fluorescent spot marking the beam location. Liquid crystal sheets have sufficient sensitivity to locate many far-infrared laser beams. Various thermal papers have been used to locate high peak power beams from pulsed visible and near-infrared lasers. Other investigator's senses have been employed to locate laser beams. A snapping sound has been heard from high peak power Nd:YAG lasers which emit below the Els for the skin. The palm of the hand has been used to follow a fairly low power CO_2 far-infrared laser beam. Fluorescence has been observed from skin when testing a 1,540 nm Erbium laser operating at a level considered safe for skin exposure.

(2) When measuring the beam, ensure that the entire beam is falling on the active surface of the detector. Systems with a large exit beam may require the use of a lens to collect all the laser emissions for the detector. Be careful not to damage the detector or any detector input optics with the focused beam. Also be sure to check the detector for linearity.

(3) The detection system with the lens should be calibrated as a unit since the addition of the lens can be complicated to analyze theoretically.

(4) Other measurement errors can be created by polarization of the laser beam in combination with optical components placed in the measurement train. Initially one should check for the presence of beam polarization by rotating a crystal polarizer in front of the detector. A variation in transmitted power or energy suggests that the beam is polarized. The maximum and minimum values during rotation should be recorded for future reference. Gelatin polarizers should not be used outside of their wavelength region which is generally confined to the visible.

(5) The investigator should observe changes in the laser output characteristics while varying user controls and record any fluctuations. It is also desirable, to measure variations in laser output power or energy with power supply voltage or current and ambient temperature. Minor variations will have little effect upon a hazard evaluation as their influence upon NOHD and protective filter OD would normally be slight.

(6) A representative sample of laser devices should be evaluated for differences in laser characteristics which may affect laser safety. Complete data from each device is not necessary unless significant variations are detected. Detailed measurements should be performed upon devices with the greatest power or energy and tightest beam divergence. The hazard analysis should incorporate the worst-case parameters from several devices.

(7) The radiometer and laser should be checked for proper operation before and after the laser measurement. A calibration check may be especially important if the radiometer were handled roughly during transit or in the field.

14. IRRADIANCE AND BEAM RADIANT EXPOSURE.

a. Measurement of Irradiance and Radiant Exposure.

(1) The irradiance or beam radiant exposure should be measured at the laser output using a 7-mm and a 5-cm to 8-cm diameter circular aperture in front of the detector and at various logarithmic distances away from the laser. To obtain the peak value of irradiance or radiant exposure in the beam, the investigator should manually scan the detector aperture within the beam for a maximum value. Be careful to control any specular reflection from the detector window which could be directed to an area with unprotected personnel.

(2) Measurements should not be performed when atmospheric turbulence is severe. A detector aperture of around 2.5-cm helps provide an average reading at long distances. When turbulence is severe it may be very difficult to measure the irradiance or radiant exposure downrange and dozens of measurements may be required.

(3) Field measurements should be avoided when the temperatures are near freezing or when the humidity is high to prevent problems with the instrumentation.

b. Check of Field Data.

(1) Before leaving the field measurement environment it is necessary for the investigator to perform a quick check to ensure that the far-field data does follow the inverse square law. This can be accomplished by plotting the calculated values of irradiance or beam radiant exposure versus range on log-log graph paper. The data should follow a smooth curve with a far-field slope of approximately 2.

(2) A calculation of beam divergence should be performed using the irradiance or radiant exposure data, effective beam diameter, radiant power or energy, and atmospheric attenuation coefficient. The divergence to 1/e should not be less than the diffraction limit, ϕ_d for a circular aperture of diameter, d:

$$\phi_d = 1.22 \frac{\lambda}{d} \qquad (6)$$

15. OTHER EXPOSURE CONDITIONS.

a. Diffuse Reflections. The potential for retinal injury from viewing a diffuse reflection of the beam must also be determined when performing a hazard evaluation. Such a viewing condition might occur when a natural object is located within the beam path at close range to the laser. When a laser device is incapable of producing a diffuse reflection hazard to the eye, this negative finding should be reported to prevent unwarranted fears. Likewise, if a potential diffuse reflection viewing hazard exists only when a lens is used to focus the beam onto a diffuse target, this finding should be reported. Such information may be important to laser maintenance personnel who might routinely fire the laser through a lens.

b. Skin Exposure. The potential for skin injury from direct exposure to the beam must also be evaluated. Just as for the diffuse reflection case, the evaluation should report negative findings and special harmful situations, such as when a lens is used to focus the beam on the skin.

c. Multiple Wavelengths. A methods has been reported for the evaluation of lasers which emit at multiple wavelengths. This method evalutes the combined effect from the multiple wavelengths upon each organ site. The techniques for evaluating multiple wavelength lasers is beyond the scope of this guide and are not describe here. Reference 16i contains more details.

d. Specular Reflections. For a conservative analysis specular reflections of the beam are treated like the direct beam. Realistically, the reflected beam may be more divergent than the incident beam. References 16g and 16j contains more details.

16. REFERENCES.

a. ANSI Z136.1-1986, Safe Use of Lasers.

b. TB MED 524, Control of Hazards to Health from Laser Radiation, 20 June 1985.

c. Title 21, Code of Federal Regulations (CFR), 1991 rev, Part 1040, Performance Standards for Light-Emitting Products.

d. MIL-STD-1425A, Safety Design Requirements for Military Lasers and Associated Support Equipment, 30 August 1991.

e. NAVSWC TR 90-665, December 1990, Laser Safety Design Requirement Checklist Adapted from MIL-STD 1425.

f. Marshall, W.J., and Conner, P.W., "Field Laser Hazard Calculations," Health Physics 52(1): 27-37, January 1987.

g. Marshall, W.J., and Van DeMerwe, W.P., "Hazardous Ranges of Laser Beams and Their Reflections from Targets," Applied Optics 25(5): 605-611, 1 March 1986.

h. Marshall, W.J., "Determining Hazard Distances from Non-Gaussian Lasers," Applied Optics 30(6): 696-698, 20 February 1991.

i. Lyon, T.L.: Hazard Analysis Technique for Multiple Wavelength Lasers. Health Physics, Vol 49, No. 2: pp 221-226 (1985).

j. Marshall, W.J., "Laser Reflections from Relatively Flat Specular Surfaces," Health Physics 56(5): 753-757, May 1989.

Terry L. Lyon
TERRY L. LYON
Physicist
Laser Microwave Division

APPENDIX A

Useful CIE Radiometric Units[1,2]

Term	Symbol	Defining equation	SI Unit and abbreviation
Radiant Energy	Q_e	$Q_e = \int \Phi_e dt$	Joule (J)
Radiant Energy Density	W_e	$W_e = \frac{dQ_e}{dV}$	Joule per cubic meter $(J \cdot m^{-3})$
Radiant Flux (Radiant Power)	Φ_e, P	$\Phi_e = \frac{dQ_e}{dt}$	Watt (W)
Radiant Exitance	M_e	$M_e = \frac{d\Phi_e}{dA} = \int L_e \cos\theta \cdot d\Omega$	Watt per square meter $(W \cdot m^{-2})$
Irradiance or Radiant Flux Density (Dose Rate in Photobiology)	E_e	$E_e = \frac{d\Phi_e}{dA}$	Watt per square meter $(W \cdot m^{-2})$
Radiant Intensity	I_e	$I_e = \frac{d\Phi_e}{d\Omega}$	Watt per steradian $(W \cdot sr^{-1})$
Radiance[3]	L_e	$L_e = \frac{d^2\Phi_e}{d\Omega \cdot dA \cdot \cos\theta}$	Watt per steradian per square meter $(W \cdot sr^{-1} \cdot m^{-2})$
Radiant Exposure (Dose in Photobiology)	H_e	$H_e = \frac{dQ_e}{dA} = \int E_e$	Joule per square meter $(J \cdot m^{-2})$
Radiant Efficiency[4] (of a source)	n_e	$n_e = \frac{P}{P_i}$	unitless
Optical Density[5]	D_e	$D_e = -\log_{10}(\tau_e)$	unitless

1. The units may be altered to refer to narrow spectral bands in which the term is preceded by the word *spectral* and the unit is then per wavelength interval and the symbol has a subscript λ. For example, spectral irradiance E_λ has units of $W \cdot m^{-2} \cdot m^{-1}$ or more often, $W \cdot cm^{-2} \cdot nm^{-1}$.

2. While the meter is the preferred unit of length, the centimeter is still the most commonly used unit of length for many of the above terms and the nm or µm are most commonly used to express wavelength.

3. At the source $L = \frac{dI}{dA \cdot \cos\theta}$ and at a receptor $L = \frac{dE}{d\Omega \cdot \cos\theta}$.

4. P_i is electrical input power in Watts.

5. τ it the transmission.

USEFUL CIE PHOTOMETRIC UNITS

Term	Symbol	Defining Equation	SI Units and Abbreviations
Luminous Energy (Quantity of Light)	Q_v	$Q_v = \int \phi \cdot v dt$	lumen-second (lm·s) or talbot
Luminous Energy Density	W_v	$W_v = \frac{dQ_v}{dV}$	talbot per cubic meter ($lm \cdot s \cdot m^{-3}$)
Luminous Flux (Luminous Power)	Φ_v	$\phi_v = 683 \int \frac{d\phi_e}{d\lambda} \cdot V(\lambda) \cdot d\lambda$	lumen (lm)
Luminous Exitance	M_v	$M_v = \frac{d\phi}{dA} = \int L_v \cdot \cos\theta \cdot d\Omega$	lumen per square meter ($lm \cdot m^{-2}$)
Illuminance (luminous flux density)	E_v	$E_v = \frac{d\phi_v}{dA}$	lumen per square meter ($lm \cdot m^{-2}$) or lux (lx)
Luminous Intensity (candlepower)	I_v	$I_v = \frac{d\phi_v}{d\Omega}$	lumen per steradian ($lm \cdot sr^{-1}$) or candela (cd)
Luminance [1]	L_v	$L_v = \frac{d^2\phi_v}{d\Omega \cdot dA \cdot \cos\theta}$	lumen per steradian per square meter ($lm \cdot sr^{-1} \cdot m^{-2}$) or candela per square meter ($cd \cdot m^{-2}$)
Light Exposure	H_v	$H_v = \frac{dQ_v}{dA} = \int E_v \cdot dt$	lux-second (lx·s)
Luminous Efficacy (radiation)	K	$K = \frac{\phi_v}{\phi_e}$	lumen per watt ($lm \cdot w^{-1}$)
Luminous Efficacy [2] (broad band radiation)	$V(*)$	$V(*) = \frac{K}{K_m} = \frac{K}{683}$	unitless
Luminous Efficacy [3] (of a source)	n_v	$n_v = \frac{\phi_v}{P_i}$	lumen per watt ($lm \cdot w^{-1}$)
Optical Density [4]	D_v	$D_v = -\log_{10} \cdot \tau_v$	unitless
Retinal Illuminance [5]	E_t	$E_t = L_v \cdot S_p$	troland (td) = luminance ($cd \cdot m^{-2}$) times the pupil area in mm^2

1. At the source $L = \frac{dI}{dA \cdot \cos\theta}$ and at a receptor $L = \frac{dE}{d\Omega \cdot \cos\theta}$.

2. $K_m = K$ at 555 nm.

3. P_i is the electrical input power in watts.

4. τ is the transmission.

5. S_p = Area of the pupil in mm^2.